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論文題目	Clarification of saline groundwater system in sedimentary rock area by geostatistical analyses of drilling investigation data （試錐調査データの地球統計学的解析による堆積岩域での高塩分地下水系の解明）		

（論文内容の要旨）

This dissertation is the results of regional characterization of hydrochemical properties of groundwater in a sedimentary rock area, clarification of their correlation with geologic structure, and interpretation of the groundwater source and chemical evolution. It is composed of six chapters.

Chapter 1 introduces this PhD research by describing the background and motivations. Accurate and comprehensive modeling of geological structure and the groundwater environment are crucial for underground construction, such as high-level radioactive waste disposal (HLW). Suitable environment for such disposal assessment requires: extremely low permeability rocks in which advective groundwater flow is essentially precluded; deep groundwater systems which have displayed stable extremely low natural advective fluxes for periods of hundreds of thousand years or longer; groundwater systems which have low fluxes combined with long transport paths away from the disposal zone to potentially accessible groundwater systems or to the biosphere. Sedimentary rocks have been studied as host rock of HLW due to favorable characteristics for the above conditions for long-term HLW disposal repositories, which have low permeability, a small diffusion coefficient, and low adsorption capacity for radionuclides. One of the main and important topic in researches for sedimentary rocks is groundwater modeling, in particular saline water. Based on these backgrounds, this research is aimed to develop the geostatistical methods to clarify saline groundwater system by selecting the Horonobe area, northern Japan as a case study site.

Chapter 2 summarizes spatial random process and methods available to regionalized, randomly sampled data, which includes spatial correlation structure by variography, kriging methods for single variable and multivariate, geostatistical process simulation, and verification of spatial modeling results.

Chapter 3 describes the details of study area with respect to topography and geologic structures, borehole investigation data at eleven sites, and the results of preliminary data processing. The size of study area is 4 km by 3 km and 1 km along the horizontal and vertical direction. 3D geological model was firstly constructed, which clarified general structures of the main geologic strata and the main fault (Omagari Fault) and its subfault.

Chapter 4 summarizes the results of spatial modeling of chemical properties. The spatial correlation structure of Cl^- concentration was ably detected by considering the dip of main (Omagari) fault in the variography. The semivariogram of Cl^- concentration and cross-semivariogram with resistivity data along the dip direction were approximated by the Gaussian model. A geostatistical simulation method could detect important features: the Omagari Fault and its subfault delineate a clear boundary between high and low Cl^- concentrations, probably from the permeable damage zones in the faults; Cl^- concentrations tended to increase with depth and reached 42–60% of seawater in deep parts below −450 m a.s.l.; the distribution of high Cl^- concentrations is consistent with shapes of the main two

strata (Koetoi and Wakkanai formations). From δD and $\delta^{18}O$ of pore-water samples, waters in deep parts with relatively heavy δD and $\delta^{18}O$ and high Cl^- concentration were inferred to originate from fossil seawater trapped in diagenetic sedimentation during the Miocene. Waters in the shallow part are mostly freshwater of meteoric water origin. The formation of a mixing zone of saline and fresh waters was found in the upper Wakkanai Formation and below the Koetoi Formation.

Chapter 5 discusses the origin and evolution of groundwater system in the study area. The dilution of water salinity in the deep part may be partially attributed to the dehydration of opal-A to opal-CT in the Wakkanai Formation and upward density flow from the deep part along a permeable damage zone in the Omagari Fault. By integrating the distributions of Cl^- concentration, δD and $\delta^{18}O$, a plausible groundwater model was constructed as follows. In the region near the Omagari Fault and its subfault, vertical flows through the faults predominate, which are down flows of meteoric waters in the shallow part and the aforementioned up flows in the deep part. In a region distant from the faults, lateral flows along small fractures, topography, and shapes of the Koetoi and Wakkanai formations are general. Consequently, the geometry and permeability of the main fault were identified as controls of groundwater flow pattern and hydrochemistry in the sedimentary rock.

Chapter 6 summarizes the main results of each chapter and future works, which includes necessary discussions on the more accurate modeling of deep groundwater system and the works to improve the spatial models of chemical properties, geological structures, and groundwater flows.

氏　名	呂　　磊

（論文審査の結果の要旨）

堆積岩は地殻表層の主要構成地質であり，CO_2 地中貯留や高レベル放射性廃棄物地層処分などで堆積岩の高い貯留機能を利用するにおいて，地表から地下深部に至る水理地質構造の詳細な把握が不可欠となる。しかしながら，これに必要な情報の量と分布は限られており，構造の断片的な理解にとどまっているのが現状である。そこで，本論文は日本原子力研究開発機構の幌延研究サイトを対象に選び，10 本の深層ボーリングコアによる間隙水の化学分析を行い，この水質データと坑井地質・物理検層データの地球統計学的空間モデリング，および得られたモデルの統合によって上記の把握を試みたものである。以下に得られた成果の概要をまとめる。

1. 坑井地質と地震探査データから複数の主要地層の 3 次元分布モデルを構築でき，各地層の変位と変形に及ぼす主断層の影響も明らかにできた。
2. 対象域の地下水の水質は Cl^- 濃度で特徴付けられ，これは断層の傾斜方位に沿って相関性が高いという Cl^- 濃度の空間的相関構造を抽出できた。Cl^- 濃度は坑井検層による比抵抗値と強い負の相関を示したので，これらと多変量地球統計学シミュレーションによって Cl^- 濃度の 3 次元分布を求めた。その結果，主断層とその副次断層が Cl^- の高濃度と低濃度の境界を形成していることがわかり，その要因として断層破砕帯が高い透水性を有するためと考えられる。また Cl^- 濃度は深度とともに増加する傾向にあり，高濃度分布は主要地層の形状に調和的である。淡水と塩水の混合層は地層の境界付近に形成されている。
3. 酸素と水素の安定同位体比の分析結果に基づくと，Cl^- 濃度が高い深部地下水は新第三紀中新世での堆積・続成作用の過程でトラップされた化石海水に起源をもつ可能性が高い。
4. 地下水中の塩分の希釈は，オパール A からオパール CT への鉱物変化に伴う脱水に起因することが示唆される。Cl^- 濃度と安定同位体比組成から，主断層付近ではこの脱水を含んだ深部からの上昇流が卓越し，それから離れると地形に沿う側方流動が主になる，という地下水流動モデルが考えられる。この妥当性を地下水流れの数値シミュレーションから確認した。よって，断層の形状と透水性が堆積岩域における地下水流動と水質を支配することを明らかにできた。

以上，本論文は，地質・地球物理・地球化学データの 3 次元モデリングと総合により，水理地質構造，地下水系，および水質分布とその形成要因を明らかにできたものであり，学術上，実際上寄与するところが少なくない。よって，本論文は博士（工学）の学位論文として価値あるものと認める。また，平成 27 年 2 月 23 日，論文内容とそれに関連した事項について試問を行い，申請者が博士後期課程学位取得基準を満たしていることを確認し，合格と認めた。